LLNL-CONF-413424

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May 29, 2009

2009 NCSD TOPICAL MEETING
Richland, WA, United States
September 13, 2009 through September 17, 2009

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Design and Criticality Considerations for 9977 and 9978 Shipping Packages

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INTRODUCTION

Savannah River National Laboratory (SRNL) has developed two new, Type B, state-of-the-art, general purpose, fissile material Shipping Packages, designated as 9977[1,2] and 9978[3], as replacements for the U.S. Department of Transportation (DOT) specification 6M container, phased out in September 30, 2008 due to non-compliance with current performance requirements specified in the Code of Federal Regulation 10 CFR Part 71. DOT 6M Specification Packages were used extensively for the transport of Type B quantities of fissile radioactive materials (uranium and plutonium metals and compounds) since the 1960's. The 9977 and 9978 shipping packages were designed as a cost-effective, user-friendly replacement. The packages accommodate plutonium, uranium, and other special nuclear materials in bulk quantities and in many forms with capabilities exceeding those of the 6M. These packages provide a high degree of single containment and comply with 10 CFR Part 71, Department of Energy (DOE) Order 460.1B, DOE Order 460.2, and 10 CFR 20 (As Low As Reasonably Achievable (ALARA)).

The packages are designed to ship radioactive contents in several configurations; Radioisotope Thermoelectric Generators (RTGs), nested food-pack cans, site-specific containers, and DOE-STD-3013 containers.

DESIGN FEATURES

The 9977/9978 General Purpose Fissile Package (GPFP) is a robust single containment package, capable of transporting plutonium and uranium metals and oxides. The design incorporates the proven Chalfont type containment vessel, employed by the widely used 9975 package. The Chalfant design is leak testable, space efficient, and very robust. The single containment 9977/9978 design meets the latest revision of 10 CFR Part 71, which eliminated the requirement for double containment for plutonium contents. For the GPFP to meet a broad range of shipping needs of the Department of Energy, the 9977/9978 is designed to accommodate materials that comply with the DOE 3013 standard or correspond to most of the contents authorized for the widely used 9975 package.

The size and weight of the 9977/9978 packages are reduced to maximize the number of packages which can be transported in a single shipment. However, if a particular content should so require, the large containment vessel (*compared to the 2R containment vessel employed by the 6M*) can accommodate a shielding 'basket' as part of the contents. The ability to accommodate various basket configurations enables providing shielding appropriate to the contents being shipped.

Each shipping package includes a 35-gallon stainless steel outer drum, insulation, a drum liner, and a single containment vessel (CV) as described in detail in the following paragraphs. The 9977 incorporates a nominal 6-inch ID CV (called 6CV) while the 9978 incorporates a 5-inch ID CV (called 5CV).

<u>DRUM (9977 and 9978)</u>

The 9977/9978 overpack (drum) body is a closed unit consisting of a shell, top deck plate, reinforcing rim (vertical flange) and a liner assembly, with the volume between the liner assembly and drum shell filled with shock-absorbing thermal-insulating materials. The drum shell and liner are fabricated of 18-gage (0.048-inch) Type 304L stainless steel (SS). One inch of Fiberfrax® insulation is wrapped around and attached to the sides and bottom of the liner. The volume between the Fiberfrax® and the drum wall is filled with polyurethane foam. The drum lid is a single piece, secured with eight bolts. The lid consists of a cap filled with ceramic insulation, the bolting flange, and a thick insulated plug that fills the upper section of the liner.

CONTAINMENT VESSEL (9977 and 9978)

The 9977 6-inch CV (or the 9978 5-inch CV) is a stainless steel pressure vessel designed, analyzed, and fabricated in accordance with Section III, Subsection NB of the ASME Code. The 5CV and 6CV are fabricated from Schedule 40, seamless, Type 304L SS pipe. Each CV is sealed with a stainless steel plug and locking nut. The steel plug (attached to the locking nut) that screws into the CV body has two O-rings that provide a leak tight seal.

The 9977 containment vessel corresponds to the 9975 secondary containment vessel while the 9978 containment vessel corresponds to the 9975 primary containment vessel. Aluminum honeycomb spacers support the smaller containment vessel within the liner for the 9978 design. Figure 1 shows important features of the 9977 and 9978.

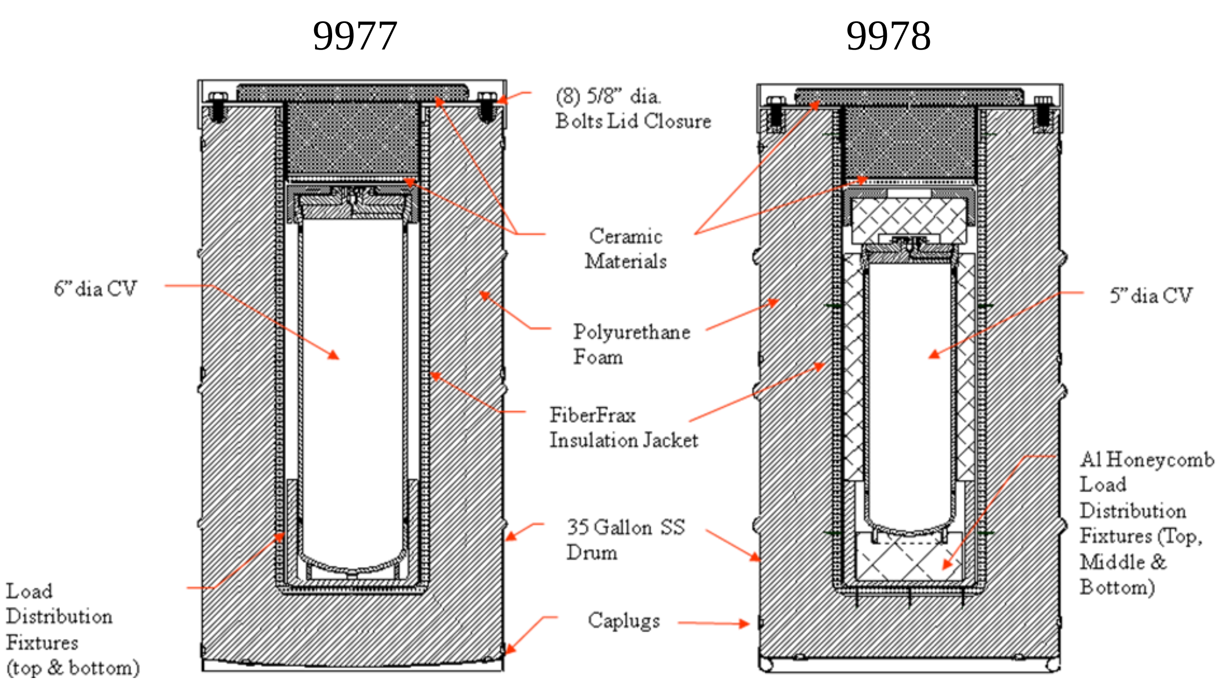

Fig. 1 – 9977 and 9978 Features

Load Distribution Fixtures (9977 and 9978)

The CV body is placed in a bottom Load Distribution Fixture (LDF). A top LDF covers the CV head. The CV and the LDFs are placed inside the steel liner. The liner is welded to the top lid flange. The LDFs are made from 6061-T6 aluminum round bar and fit within the Drum Liner cavity. The LDFs center the CV in the liner, stiffen the package in the radial direction, and distribute loads away from the CV. The 6CV for the 9977 fits directly into the LDFs while aluminum honeycomb spacers position the 5CV in the LDFs for the 9978.

Honeycomb Spacers (9978 only)

Three aluminum Honeycomb Spacers center the 5CV within the two LDFs and position the 5CV within the overpack liner cavity. The Spacers are manufactured from minimum 3-mil thick 5052 aluminum honeycomb. The top surface of the Lower Spacer is embossed with the 5CV bottom configuration (i.e., the cap and skirt) and is covered by a 0.050-inch layer of fiberglass for wear protection. The Bottom LDF, the Annular Spacer, and the Lower Spacer are fabricated as an assembly.

Table 1 summarizes important design features of 9977 and 9978 and compares them with those of 9975.

Table 1 – Comparison of 9977 and 9978 with 9975

Package.	9975	9977	9978
Drum Size (gallons)	35	35	35
Drum Diameter (inches)	18.35	18.35	18.35
Drum Height (inches)	36.1	36.1	36.1
Maximum Gross Weight	404 lb	350 lb	285 lb
Maximum Content Weight	44.4 lb	100 lb	50 lb
Containment	Double	Single	Single
CV Diameter (inches)	6 and 5	6	5
Shielding	½ inch lead	none	none
Content Envelope	4.4 kg Pu / 13.5 kg U	4.4 kg Pu / 16.0 kg U	4.4 kg Pu / 13.5 kg U
CSI	2.0	1.0	1.0

CRITICALITY EVALUATION

Design features of the 9977 and 9978 supporting criticality safety include the CV dimensions, which limit geometry and volume occupied by fissile material, and the drum size and configuration, which maintains spacing between contents of adjacent packages. There are no other criticality control design features (e.g., neutron absorbers, flux traps). Allowed package contents were determined accounting for nuclear criticality, radiation shielding, and decay heat rate. The criticality safety index (CSI) of 1.0 for all but content C.1 maximizes flexibility during transportation. Content C.1 (100 grams of Pu-238) has a CSI of 0.

Methodology

The SCALE 5 / KENO VI code system operating on the WSMS Linux Workstation Cluster was used to calculate k_{eff} values. The 238-group ENDF/B-V cross section set was used for all calculations. SCALE 5 has been validated for plutonium metal and oxide, plutonium solutions, highly enriched uranium (HEU) metal, HEU oxide, and HEU solution systems on the WSMS Linux system. The NUREG document[3] specifies a minimum required margin of subcriticality of 0.05 for packaging applications. Based on the fact that a large Minimum Subcritical Margin (MSM) has been used for the 9977 and 9978 analysis for common fissile materials (i.e., ^{239}Pu and ^{235}U) and drum materials, no additional margin due to 'areas of applicability' is necessary. Table 2 shows the biased k_{eff} and k_{safe} values for various systems. The lowest k_{safe} value of 0.931 was used in the criticality safety analysis.

Table 2: Validation Biased K_{eff} and K_{safe} Values

System	Biased k_{eff} Value	MSM	k_{safe}
Plutonium Metal	0.981	0.05	0.931
Uranium Metal	0.981^{+}	0.05	0.931
Plutonium Solution	0.997	0.05	0.947
Uranium Solution	0.991	0.05	0.941
Plutonium Oxide, dry	0.996	0.05	0.946
Uranium Oxide, dry	0.988	0.05	0.938

Fissile Material Contents for 9977 and 9978 Package

a. 9978 Contents

The 9978 is analyzed for the transport of five content envelopes, described in the following.

Envelope	Description
C.1	Mainly Plutonium-238 Oxide Heat Sources (100 grams or less).
C.2	Plutonium and/or Uranium Metal (4.4 kg of Pu/U).
C.3	Plutonium and/or Uranium Oxides (**Reserved,** Not Requested in 9978 Rev. 1).
C.4	Uranium Metals or Alloys (13.5 kg of ^{235}U).
C.5	Uranium Compounds (oxides only with varying H/X atom ratios with a maximum of 4.4 kg of ^{235}U).
C-6	Samples and Sources (12.75 kg of radioisotopes, with 12 kg being the non-fissile isotopes ^{238}U or ^{232}Th, leaving only 0.75 kg for other radioisotopes, significantly less than the 4.4 kg of fissile material analyzed for Content Envelope C.2. Three fissionable isotopes are allowed in gram quantities in Content Envelope C.6 that are not permitted in Content Envelope C.2, ^{241}Am, ^{243}Am, and ^{237}Np.

b. 9977 Content

A single content is allowed for the 9977, Content Envelope C.1, Heat Sources, in assemblies of Radioisotope Thermoelectric Generators or food-pack cans with radioactive contents of 100 grams or less, mainly ^{238}Pu. The maximum allowable radioactive decay heat is 19 W.

c. 9977 Addendum 1 (with Sleeve and Plug design)

Addendum 1, Justification for Domestic Nuclear Detection Office (DNDO) Contents, supplements Revision 2 of the Safety Analysis Report for Packaging for the Model 9977 Package. The submittal adds five new contents to the Model 9977 Package, Content Envelopes, AC.1 through AC.5.

Envelope	Description
AC.1	Neptunium Metal (up to 6,070 g).
AC.2	BeRP Ball (4500 gram).
AC.3	Plutonium/Uranium Metal (4,400 g)
AC.4	Plutonium/Uranium Metal (limited to 2,000 g. The metal must be stabilized per DOE-STD-3013. The maximum ^{240}Pu is 50 wt%, in contrast to Content Envelope AC.3 where the maximum ^{240}Pu is 25 wt%).
AC.5	Uranium Metal (16,000 g for ^{235}U enrichments of up to 100 wt%, or 18,000 g, for ^{235}U enrichments of up to 95 wt%)

9977 and 9978 Packaging Requirement

The contingencies that are to be considered for the 9977/9978 shipping package criticality analysis are specified in 10 CFR 71. Specifically, the objective of the evaluation is to demonstrate compliance with the performance requirements for each content envelope as specified in

- 10 CFR 71.55 – General requirements for fissile material packages, and
- 10 CFR 71.59 – Standards for arrays of fissile material packages.

The requirements of 10 CFR 71 are thorough and ensure that the maximum value of k_{eff} is found in the analysis based on credible scenarios. The following specific scenarios are analyzed based on the 10 CFR 71 requirements:

Single Package (SP) – dry and flooded
Normal Conditions of Transport (NCT) array – dry and flooded
Hypothetical Accident Conditions (HAC) array – dry and flooded

Assumptions for Criticality Evaluation

The following conservative modeling choices are used in the criticality analysis for the shipping packages:

i) Water is assumed to leak into the Containment Vessel (CV) as well as the overpack package container for the single package (SP) analysis. The CV remains dry during the normal conditions of transport (NCT) and the hypothetical accident conditions (HAC).

ii) The HAC model included reduction of package diameter and height due to drop and crush as well as loss of foam insulation during fire and extreme movement of the 5CV within the drum. The modeled reductions in dimensions and loss of foam are based on the 9977/9978 shipping package drop test data and the foam burn data from the actual test reports.

iii) A mass of 100 grams of polyethylene is modeled as closely wrapped around the plutonium/uranium metal for several configurations. Polyethylene $(C_2H_4)_n$ is modeled with a density not exceeding 0.95 g/cc.

iv) The plutonium isotopic composition is 100% ^{239}Pu. The uranium isotopic composition is 100% ^{235}U.

9978 Single Package (SP) – Intact Fissile Material Cases – Model and Analyses

Only cases for the 9978 with the 5CV are discussed. The 9977 cases (with the plug and sleeve in the 6CV) are similar. The SP base case model considered the fissile material without containers inside the containment vessel. Fissile contents of plutonium metal, uranium metal, plutonium oxide and uranium oxide were modeled in the form of a sphere at the bottom of the 5CV. Variations of the base case with plutonium metal were modeled to examine the effects of presence of the 3013 container, location of fissile material within the 5CV, and polyethylene material surrounding the fissile sphere representing the presence of plastic commonly associated with a non-3013 (food pack) can.

Table 3 presents the results for the SP study. All the cases resulted in a $k_{eff}+2\sigma$ values less than the k_{safe} of 0.931. Thus, a maximum of 4.4 kg ^{239}Pu or 13.5 kg ^{235}U will remain subcritical in all SP cases. These cases show that the 9978 with plutonium metal results in the highest k_{eff} values compared to cases with uranium metal (compare case 1 with case 5, and case 2 with case 6). Oxide cases are less reactive. 100 g of polyethylene increases the $k_{eff}+2\sigma$ values by only about 0.0071 (compare case 2 and case 3).

Table 3: 9978 Single Package – Dry/flooded Cases

Case No.	Description	k_{eff} + 2σ
1	Dry bare 4.4 kg ^{239}Pu metal sphere centered in bottom of CV, drum reflected by 30 cm of water	0.8080
2	Case 1, with drum and CV flooded	0.9185
3	Case 2 with 100 g polyethylene surrounding fissile sphere	0.9256
4	Case 1 with dry3013, drum and CV flooded	0.8304
5	Dry bare 13.5 kg ^{235}U metal sphere centered in bottom of CV	0.7397
6	Case 5, with drum and CV flooded	0.8380

Note: Except as noted, in all cases water fills the CV. The drum walls and drum insulation are replaced by water.

The 3013 container is comprised of a convenience can located inside two nested sealed (welded) inner and outer containers. In general, the addition of these three stainless steel cans adds a small amount of stainless steel inside the CV, which provides the competing effects of increasing neutron absorption and reflection by small amounts. The calculated k_{eff}+2σ value, in general, increases by about 1% for a dry CV. The k_{eff}+2σ value decreases for a flooded CV with a 3013 (case 4), as the presence of a 3013 decreases the amount of water available as a reflector inside the 5CV as no water is modeled inside the 3013.

SP Solution Cases

It should be noted that immersion will not result in water in-leakage into the 5CV of a 9978 package. This was demonstrated by the fact that the HAC test with the 30-foot drop, puncture, impact and fire resulted in no observable containment vessel deformation, which otherwise could result in in-leakage. In-leakage, if it were to occur, would likely be through the seal region of the 5CV. Testing has shown that the seal region is helium leak tight following the sequential drop, puncture, and fire tests. However, flooding in the SP analysis was considered in order to examine the most adverse condition and to comply with 10 CFR 71.

The SP solution cases explicitly modeled a 5CV with a specified fissile mass and varied the fissile concentration. Fissile mass values less than the maximum specified by the content envelopes were modeled to achieve lower fissile concentrations. The maximum fissile concentration was limited to a value slightly less than the maximum theoretical density for the fissile metal. The minimum fissile concentration was limited by the maximum volume of the 5CV, about 5.1 liters. Table 4 summarizes the analysis results.

Table 4: Single Package – Solution Cases – Plutonium

Case No.	Mass ^{239}Pu (kg)	Concentration (kg/L)	Solution Height (cm)	k_{eff} + 2σ
1	4.4	0.86823	37.51	0.8016
2	4.4	1	32.339	0.7993
3	4.4	1.5	20.977	0.7830
4	4.4	5	5.069	0.7278
5	4.4	10	1.661	0.7573
6	4.4	15	0.524	0.8163
7	4.4	18	0.146	0.8619

Comparison of Table 3 and Table 4 indicates that the flooded bare metal sphere configuration bounds the same fissile mass in solution in a 5CV since the metal sphere produces a higher reactivity than the solution in a 5CV. The system reactivity tends to increase as the mixture density approaches that of metal. The system reactivity increases as the fissile concentration decreases and solution height in the 5CV increases to correspond to the maximum allowed volume.

Table 5 shows the k_{eff} results for ^{235}U solution cases, demonstrating that a 13.5 kg ^{235}U mass will remain subcritical inside the 5CV even if water leaks into the 5CV and mixes with the fissile material. The primary basis of this condition is the volume limitation provided by the 5CV. The fissile material solution in the 5CV is under moderated due to the restricted volume of the 5CV.

Table 5: Single Package – Solution Cases – Uranium

Case No.	Mass ^{235}U (kg)	Concentration (kg/L)	Solution Height (cm)	k_{eff} + 2σ
1	13.5	2.66386	37.51	0.8460
2	13.5	5	19.169	0.8276
3	13.5	10	8.710	0.8107
4	13.5	15	5.224	0.8191
5	13.5	18	4.062	0.8344

Scoping calculations indicated that the volume of a 6CV was sufficient to allow the maximum system k_{eff} +2σ values to occur at lower fissile concentrations than shown in Table 4 or Table 5 and exceeds the k_{safe} value. Therefore a plug and sleeve design was specified in the 9977 Addendum 1 to restrict the 6CV volume to approximate that of the 5CV. Figure 2 shows the plug and sleeve design introduced in Addendum 1.

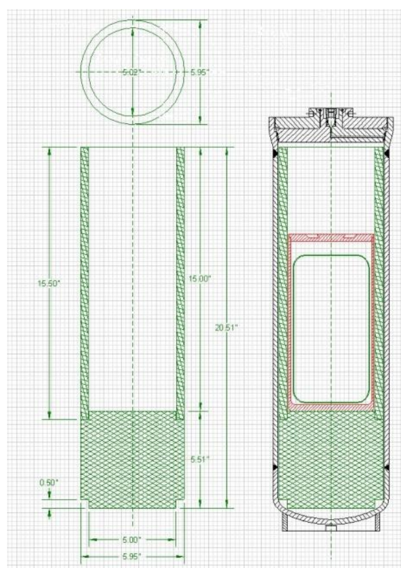

Fig. 2: Aluminum Plug and Sleeve for 6CV

9978 Normal Conditions of Transport (NCT) Array Analyses

In the NCT undamaged package array model, the package was modeled with the nominal dimensions. An infinite square pitch array of stacked packages with dry and partially flooded conditions was modeled unless specified otherwise. The flooded conditions studied for the NCT analysis modeled water in the liner and insulation regions. The 9978 was modeled with water in the liner and insulation regions. This is conservative since tests per 10 CFR § 71.71(c)(6) indicate that only the liner region can retain water. The 9978 model used the 6CV containment vessel, as the distance between the interacting fissile masses would not be affected by the CV dimensions. The infinite square pitch array was simulated by modeling a single package in a cuboid. This outer region was assigned mirror reflection boundaries in the x and y directions, and periodic boundary conditions in the z direction. Some cases specifically modeled a 6x6x7 array of 9977 packages with 30 cm of full density water reflection surrounding the array. Such cases were less reactive than the infinite array cases. Table 6 summarizes the k_{eff} results for infinite array.

Table 6: NCT Infinite Array Configuration Results

CaseNo.	Description	k_{eff} +2σ
1	4.4 kg ^{239}Pu metal surrounded by a 100 g poly shell	0.8526
2	4.4 kg ^{239}Pu metal sphere surrounded by a 100 g poly shell in a 3013, and drum flooded, water between the packages	0.8536
3	4.4 kg ^{239}Pu metal sphere surrounded by a 100 g poly shell in a 3013, and drum and CV flooded, water between the packages	0.8741
4	4.4 kg ^{239}Pu metal sphere surrounded by a 100 g poly shell in a 3013, water only between the packages	0.8515
5	Same as case 4, no water between packages	0.8646
6	13.5 kg ^{235}U metal sphere surrounded by a 100 g poly shell	0.7981

The results show that all NCT cases are subcritical. The packages are more isolated when there is interstitial water between packages (compare case 4 and case 5). Note there is no water is inside the 3013 container.

9978 Hypothetical Accident Conditions (HAC) Analyses

For the HAC analyses, a 6x6x3 square pitch array of 9977 packages was modeled as reflected by 30 cm of water in all six directions. The 9977 packages were modeled under the prescribed accident conditions. Each 9977 package contained a 4.4 kg ^{239}Pu sphere that was surrounded by 100 g polyethylene. The 6CV was used in the HAC models for 9977 as well as 9978 cases for conservatism.

Array analyses were performed using a 7% reduced drum radius to approximate an equivalent triangular pitch array configuration. This 7% radius reduction was in addition to the damage values demonstrated by the test results. Test results indicate that a 2” (5.08 cm) reduction in the package diameter and a 2” (5.08 cm) reduction in the package height bound the HAC model.

Table 7 summarizes the HAC results. Each of the cases in Table 7 that reduced the diameter, the height, or both, resulted in a smaller volume for the foam region. The foam density was not increased to conserve mass in the foam region due to the reduced volume of the foam region. Some cases studied the absence of the foam, thus eliminating the need for a parametric study of the system reactivity versus foam density.

Figure 3 depicts a top view of the normal 6x6x3 square pitch array used in the HAC analysis. The normal configuration reduced the outer package dimensions but did not shift the interior contents. Fig. 4 depicts a systematic shift in the interior contents where the distance between the fissile content in every pair of packages was minimized. Figure 5 extended the concept to groups of four packages. The primary purpose of the two-group and four-group cluster models was to analyze the need for relying on the construction materials and design to maintain the CV integrity and location inside the package. In the 2-cluster and 4-cluster models, the mass of the insulation was conserved when compared to the centered configuration, since the models simply shifted the container contents.

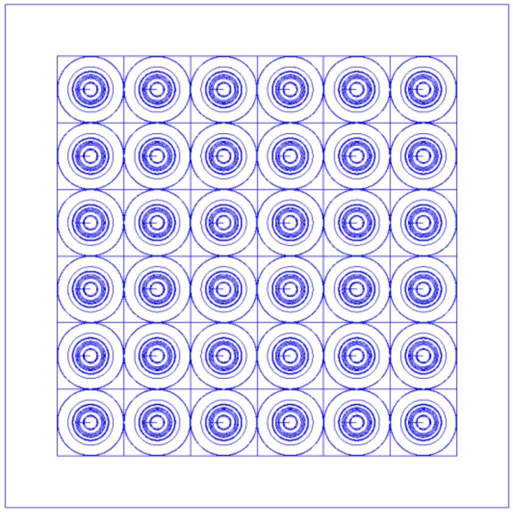

Fig. 3: Centered Array

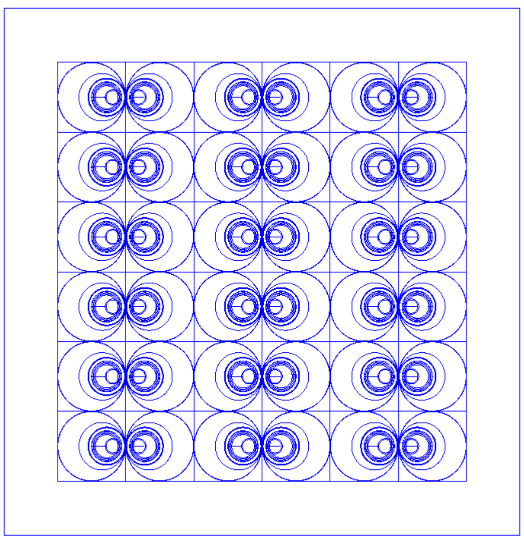

Fig. 4: Two Cluster HAC Model

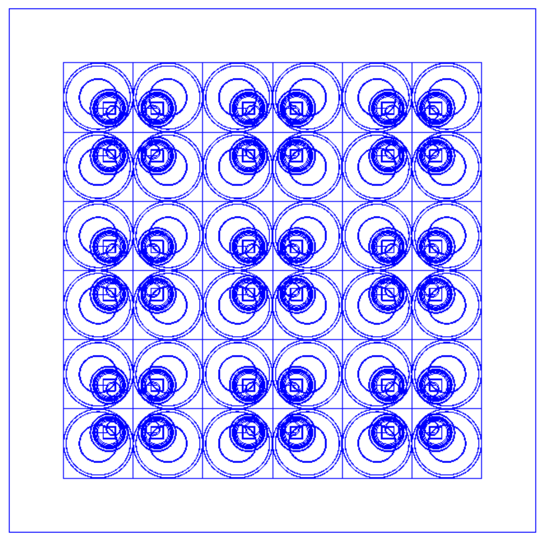

Fig. 5: Four Cluster HAC Model

The HAC series of calculations reported in Table 7 begin with a NCT package in a 6x6x3 array. The study removed insulation, reduced radius and height corresponding to damage, further reduced the radius to approximate a triangular pitch array, and modeled the contents of the packages in two positions to maximize the interaction of the fissile material in the package.

Table 7: HAC Analysis Results

Case No.	Description	$k_{eff}+2\sigma$
1	6x6x3 square pitch array of drums in contact, array reflected with 30 cm of water in all 6 directions, each drum with 4.4 kg ^{239}Pu sphere surrounded by 100 g polyethylene, no 3013, nominal container dimensions; normal presence of foam, Fiberfrax, Vermiculite and Min-K 2000, fissile sphere radially centered in drum. See Fig. 3.	0.8397
2	Identical to case 1 but reduced container OD by 2" and the outer height was reduced 2" (1" top and bottom) corresponding to HAC conditions. See Fig. 3.	0.8502
3	Identical to case 2 but no foam present (all other insulators were present)..	0.8630
4	6x6x3 square pitch array of drums, array reflected by 30 cm water, each drum with 4.4 kg ^{239}Pu sphere radially centered in drum surrounded by 100 g polyethylene, no 3013; no foam, Fiberfrax, Vermiculite or Min-K 2000 present; HAC diameter from case 2 was reduced by 7% to approximate triangular pitch array; HAC top height was reduced by 1".	0.8659
5	Same as case 4 but created pairs (2-cluster model). See Fig. 4.	0.8895
6	Same as case 4 but created groups of four drums (4-cluster model). See Fig. 5.	0.8846
8	Same as case 5 but water fills the liner, and foam regions in the 9977, and between packages in the array.	0.8660

All of the cases in Table 7 resulted in $k_{eff}+2\sigma$ values significantly less than k_{safe}. This directly demonstrates that a maximum of 4.4 kg ^{239}Pu as metal will remain subcritical inside the 9977 (or 9978) package under HAC conditions. An analysis with 4.4 kg ^{239}Pu as metal provides a bounding analysis for 13.5 kg ^{235}U as metal. Therefore, the 10 CFR § 71.55(e) and § 71.59(a)(2) requirements related to HAC analyses are satisfied.

Criticality Safety Index

The calculation of the CSI for the NCT is conservatively based on the 6x6x7 array size and for the HAC is based on the 6x6x3 array size. The CSI calculations for NCT and HAC are shown in parallel in Table 8.

Table 8: CSI Calculation

Calculate the value of N for NCT: 5*N = 6x6x7 = 252 so N = 252/5 = 50.4 The CSI is defined by 10 CFR §71.59 as, CSI ≡ 50/N = 50/50.4 = 0.992 Rounding up to the first decimal we get, CSI = 1.0	Calculate the value of N for HAC: 2*N = 6x6x3 = 108 so N = 108/2 = 54 The CSI is defined by 10 CFR §71.59 as, CSI ≡ 50/N = 50/54 = 0.926 Rounding up to the first decimal we get, CSI = 1.0

Since the CSI calculations in Table 8 derive the same CSI value for NCT and HAC configurations, the CSI is equal to 1.0 for the 9978 package for the approved content envelopes (and also for the 9977 packages with the plug and sleeve design).

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2. Safety Analysis Report for Packaging, Model 9977, Addendum 1, S-SARA-G-00003, Rev. 2, October 2008.

3. Safety Analysis Report for Packaging, Model 9978, S-SARP-G-00002, Rev. 1, March 2009.

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This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344